

THE LOW DENSITY TRANSITING EXOPLANET WASP-15B

R. G. WEST¹, D. R. ANDERSON², M. GILLON^{3,4}, L. HEBB⁵, C. HELLIER², P. F. L. MAXTED², D. QUELOZ³, B. SMALLEY²,
A. H. M. J. TRIAUD³, D. M. WILSON², S. J. BENTLEY², A. COLLIER CAMERON⁵, B. ENOCH⁵, K. HORNE⁵, J. IRWIN⁶,
T. A. LISTER⁷, M. MAYOR³, N. PARLEY⁵, F. PEPE³, D. POLLACCO⁸, D. SEGRANSAN³, S. UDRY³, AND P. J. WHEATLEY⁹

Draft version February 16, 2009

ABSTRACT

We report the discovery of a low-density exoplanet transiting an 11th magnitude star in the Southern hemisphere. WASP-15b, which orbits its host star with a period $P = 3.7520656 \pm 0.0000028$ d has a mass $M_p = 0.542 \pm 0.050 M_J$ and radius $R_p = 1.428 \pm 0.077 R_J$, and is therefore the one of least dense transiting exoplanets so far discovered ($\rho_p = 0.247 \pm 0.035 \text{ g cm}^{-3}$). An analysis of the spectrum of the host star shows it to be of spectral type around F5, with an effective temperature $T_{\text{eff}} = 6300 \pm 100 \text{ K}$ and $[\text{Fe}/\text{H}] = -0.17 \pm 0.11$.

Subject headings:

1. INTRODUCTION

Transiting exoplanets represent the best current opportunity to test theoretical models of the internal structure of such planets, and the formation and evolution of planetary systems. At the time of writing the discovery of approaching sixty transiting systems had been announced in the literature by numerous well-established survey projects, such as HATnet (Bakos et al. 2004), XO (McCullough et al. 2005), TrES (O'Donovan et al. 2006) and WASP (Pollacco et al. 2006).

The WASP project operates two identical observatories, one at La Palma in the Canary Islands, and the other at Sutherland in South Africa. Each telescope has a field of view of approximately 500 square degrees. The WASP survey is capable of detecting planetary transit signatures in the light-curves of hosts in the magnitude range $V \sim 9\text{--}13$. A full description of the telescope hardware, observing strategy and pipeline data analysis is given in Pollacco et al. (2006).

2. OBSERVATIONS

The host star WASP-15 (= 1SWASP J135542.70-320934.6 = 2MASS 13554269-3209347 = USNO-B1.0 0578-0402627 = NOMAD1 0578-0409366 = TYCH2 7283-01162-1) is catalogued as a star of magnitude $V = 11.0$ and co-ordinates $\alpha = 13^{\text{h}}55^{\text{m}}42^{\text{s}}.71$, $\delta = -32^{\circ}09'34''.6$. WASP-15 was observed by the

WASP-South observatory in a single camera field from 2006 May 04 to 2006 July 17, and in two overlapping camera fields from 2007 January 31 to 2007 July 17 and from 2008 January 31 to 2008 May 29.

The data were processed using the project's routine analysis pipeline, de-trending and transit-detection tools as described in Pollacco et al. (2006), Collier Cameron et al. (2006) and Collier Cameron et al. (2007). A total of 24943 data points were acquired, in which was detected a recurrent transit signature with a period of 3.7520 days and a depth of 0.011 mag (Fig. 1, top panel). In total some 11 full or partial transits were observed by WASP-South.

Follow-up photometric observations were made using the EulerCAM photometer on the 1.2m Euler telescope in the I-band on 2008 March 29 and the R-band on 2008 May 13 (Fig. 1 middle and lower panel), which confirmed the presence of a flat-bottomed dip expected from the transit of an exoplanet. Both transit light-curves from EulerCAM exhibit excess variability likely due to systematic noise.

Subsequent observations using the CORALIE spectrograph on the Euler telescope between 2008 March 06 and 2008 July 17 yielded 21 radial-velocity measurements (Table 1; Fig. 2 upper panel) which show a sinusoidal variation with a semi-amplitude of around 65 m s^{-1} on the same period as the transit signature. An analysis of the bisector spans (Fig. 2 lower panel) shows no correlation with the measured radial velocity, which rules out the possibility that the RV variations were due to a blended eclipsing binary system.

3. EVOLUTIONARY STATUS OF THE HOST STAR

The individual CORALIE spectra are relatively low signal-to-noise, but when co-added into 0.01Å steps they give a S/N of around 80:1 which is suitable for a photospheric analysis of WASP-15. In addition, a single HARPS spectrum was used to complement the CORALIE analysis, but this spectrum had relatively modest S/N of around 50:1.

An analysis of the available spectral data was performed using the UCLSYN spectral synthesis package (Smith 1992; Smalley 2001) and ATLAS9 models without convective overshooting (Castelli et al. 1997). The H_{α}

¹ Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK

² Astrophysics Group, Keele University, Staffordshire, ST5 5BG, UK

³ Observatoire de Genève, Université de Genève, 51 Chemin des Maillettes, 1290 Sauverny, Switzerland

⁴ Institut d'Astrophysique et de Géophysique, Université de Liège, Allée du 6 Août, 17, Bat. B5C, Liège 1, Belgium

⁵ School of Physics and Astronomy, University of St. Andrews, North Haugh, Fife, KY16 9SS, UK

⁶ Department of Astronomy, Harvard University, 60 Garden Street, MS 10, Cambridge, Massachusetts 02138, USA

⁷ Las Cumbres Observatory, 6740 Cortona Dr. Suite 102, Santa Barbara, CA 93117, USA

⁸ Astrophysics Research Centre, School of Mathematics & Physics, Queen's University, University Road, Belfast, BT7 1NN, UK

⁹ Department of Physics, University of Warwick, Coventry, CV4 7AL, UK

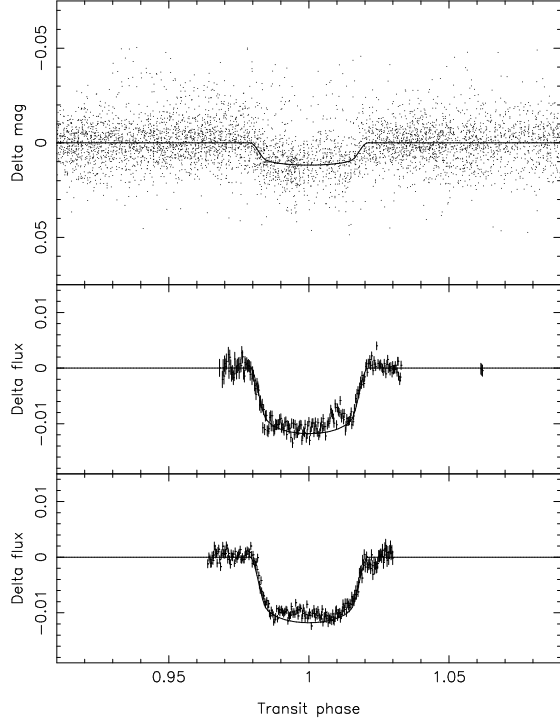


FIG. 1.— WASP photometry folded on the best-fit period (top panel). EULER I-band (middle) and R-band (lower). Curve shows the best-fit transit model from the MCMC fitting.

TABLE 1
RADIAL VELOCITY MEASUREMENTS OF WASP-15

BJD −2 400 000	RV (km s ^{−1})	σ_{RV} (km s ^{−1})	BS (km s ^{−1})
54531.8146	−2.3020	0.0148	0.0042
54532.7221	−2.3914	0.0180	0.0392
54533.7468	−2.3747	0.0151	0.0209
54534.8778	−2.2799	0.0150	0.0100
54535.7341	−2.3090	0.0137	−0.0494
54536.6666	−2.4124	0.0126	0.0156
54537.7805	−2.3671	0.0099	0.0107
54538.7459	−2.2886	0.0108	0.0009
54556.7948	−2.3156	0.0112	0.0011
54557.7488	−2.2825	0.0133	0.0010
54558.7334	−2.3925	0.0105	0.0055
54559.7479	−2.3923	0.0109	0.0120
54560.6158	−2.3144	0.0118	−0.0067
54589.6590	−2.4257	0.0126	−0.0108
54591.6355	−2.2959	0.0118	0.0046
54655.4689	−2.2933	0.0110	0.0316
54656.5165	−2.3761	0.0106	0.0489
54657.6134	−2.3190	0.0157	0.0171
54662.5205	−2.2760	0.0095	0.0538
54663.5879	−2.3634	0.0132	0.0451
54664.5932	−2.3879	0.0146	0.0126

and $H\beta$ lines were used to determine the effective temperature (T_{eff}), while the Na I D and Mg I b lines were used as surface gravity ($\log g$) diagnostics. Additionally, the Ca H & K lines provide a further check on the derived T_{eff} and $\log g$. This fit yielded a $T_{\text{eff}} = 6300 \pm 100$ K and $\log g = 4.35 \pm 0.15$ (Table 2).

In order to determine the elemental abundances the equivalent widths of several clean and unblended lines were measured. Atomic line data were mainly taken from the Kurucz & Bell (1995) compilation, but

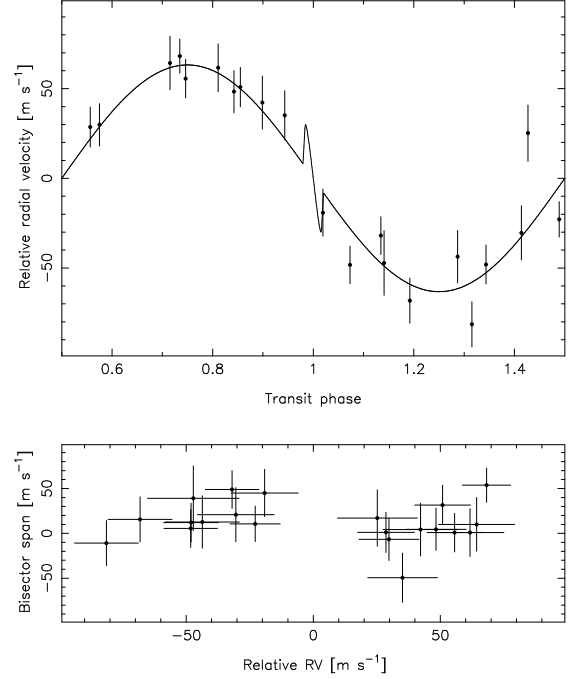


FIG. 2.— CORALIE radial-velocity measurements. Curve shows best-fit MCMC model. Lower panel shows the bisector span plotted against RV.

with updated van der Waals broadening coefficients for lines in Barklem et al. (2000) and $\log gf$ values from Gonzalez & Laws (2000), Gonzalez et al. (2001) or Santos et al. (2004). A value for microturbulence (ξ_t) was determined from Fe I using the method of Magain (1984). The ionization balance between Fe I and Fe II and the null-dependence of abundance on excitation potential were used in addition to the T_{eff} and $\log g$ diagnostics (Smalley 2005). The abundances are given in Table 2. The quoted error estimates include that given by the uncertainties in T_{eff} , $\log g$ and ξ_t , as well as the scatter due to measurement and atomic data uncertainties. The Li I 6708Å line is not detected ($\text{EW} < 2\text{mÅ}$), allowing us to derive an upper-limit on the lithium abundance of $\log n(\text{Li}/\text{H}) + 12 < 1.2$. The T_{eff} of this star implies it is in the lithium-gap (Böhm-Vitense 2004), so the lithium abundance does not provide an age constraint.

Stellar rotation velocity ($v \sin i$) was determined by fitting the profiles of several unblended Fe I lines in the HARPS spectrum. A value for macroturbulence (v_{mac}) of 4.8 km s^{-1} was adopted, from the Valenti & Fischer (2005) relationship, and an instrumental FWHM of $0.060 \pm 0.005 \text{ Å}$, determined from the telluric lines around 6300Å. A best fitting value of $v \sin i = 4 \pm 2 \text{ km s}^{-1}$ was obtained.

To estimate the age of WASP-15 we compared the stellar density and temperature measured from the photometric and spectroscopic analysis against the evolutionary models of Girardi et al. (2000) interpolated to a metallicity $[M/H] = -0.17$ (Fig. 3). This procedure yields a best-fit age of $3.9^{+2.8}_{-1.3}$ Gyr and a best-fit mass $M_* = 1.19 \pm 0.10 M_{\odot}$.

4. SYSTEM PARAMETERS AND DISCUSSION

The available WASP-South and EulerCAM photometric data were combined with the CORALIE radial-velocity measurements in a simultaneous Markov-

TABLE 2
PARAMETERS OF THE HOST STAR

Parameter	Value
Stellar mass, M_* (M_\odot)	1.18 ± 0.12
Stellar radius, R_* (R_\odot)	1.477 ± 0.072
Stellar surface gravity, $\log g^a$ (cgs)	4.169 ± 0.033
Stellar density, ρ_* (ρ_\odot)	0.365 ± 0.037
Stellar luminosity, L_* (L_\odot)	3.09 ± 0.34
Age (Gyr)	$3.9^{+2.8}_{-1.3}$
T_{eff} (K)	6300 ± 100
$\log g^b$	4.35 ± 0.15
ξ_t (km s^{-1})	1.4 ± 0.1
$v \sin i$ (km s^{-1})	4 ± 2
[Fe/H]	-0.17 ± 0.11
[Na/H]	-0.25 ± 0.05
[Mg/H]	-0.13 ± 0.12
[Si/H]	-0.15 ± 0.10
[Ca/H]	-0.06 ± 0.13
[Sc/H]	-0.07 ± 0.12
[Ti/H]	-0.14 ± 0.06
[V/H]	-0.20 ± 0.11
[Cr/H]	-0.11 ± 0.12
[Co/H]	-0.16 ± 0.08
[Ni/H]	-0.25 ± 0.08
$\log N(\text{Li})$	< 1.2

^a Derived from MCMC analysis ^b Derived from spectral analysis

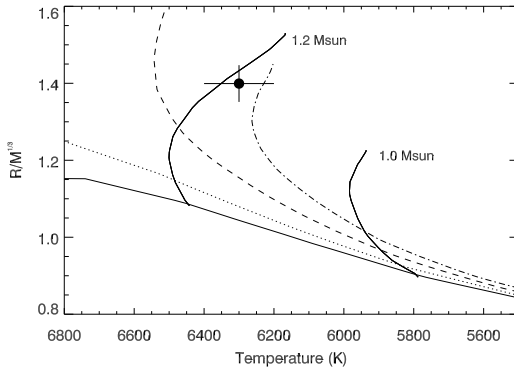


FIG. 3.— The position of WASP-15 in the $R/M^{1/3}-T_{\text{eff}}$ plane. Evolutionary tracks for a star of metallicity $[M/H] = -0.17$ from Girardi et al. (2000) are plotted along with isochrones for ages 100 Myr (solid), 1 Gyr (dotted), 2.5 Gyr (dashed) and 4 Gyr (dot-dashed). Evolutionary mass tracks are shown for 1.0 and 1.2 M_\odot .

Chain Monte-Carlo (MCMC) analysis, as described in Collier Cameron et al. (2007). An initial run yielded a best-fit value for the orbital eccentricity nearly consistent with zero ($e = 0.052^{+0.029}_{-0.040}$), so a further fit was made with the eccentricity fixed to zero. We chose not to excise from the fit any data points in the EulerCAM light-curves affected by systematics; nevertheless the fitted model light-curves (Fig. 1) globally do not appear to have been adversely perturbed by these features.

The best-fit system parameters are listed in Tables 2 and 3 and reveal WASP-15b to be a planet with one of the lowest densities yet measured, comparable to TrES-4 (Mandushev et al. 2007; Sozzetti et al. 2008). The planetary radius measured here lies above that predicted by the models of Fortney et al. (2007) and Burrows et al. (2007) for a coreless planet of the mass, age and insolation of WASP-15b. An additional internal heat source

TABLE 3
PARAMETERS OF THE PLANET AND ORBIT

Parameter	Value
Transit epoch (BJD), T_C	$2454584.69823 \pm 0.00029$
Orbital period, P (d)	3.7520656 ± 0.0000028
Transit duration, T_{14} (d)	0.1548 ± 0.0014
Planet/star area ratio, R_p^2/R_*^2	0.0099 ± 0.0002
Impact parameter, b (R_*)	$0.568^{+0.038}_{-0.046}$
Stellar reflex vel., K_1 (km s^{-1})	0.0634 ± 0.0038
Centre-of-mass vel., γ (km s^{-1})	-2.3439 ± 0.0005
Orbital separation, a (AU)	0.0499 ± 0.0018
Orbital inclination, i (deg)	85.5 ± 0.5
Orbital eccentricity, e	$\equiv 0$ (adopted)
Planet mass, M_p (M_J)	0.542 ± 0.050
Planet radius, R_p (R_J)	1.428 ± 0.077
Planet surface gravity, $\log g_p$ (cgs)	2.784 ± 0.044
Planet density, ρ_p (ρ_J)	0.186 ± 0.026
Planet density, ρ_p (cgs)	0.247 ± 0.035
Planet equil. temp. ($A=0$), T_p (K)	1652 ± 28

such as tidal dissipation may be required in order to account for this anomalously large radius. Indeed Liu et al. (2008) have recently shown that only moderate tidal heating would be required to explain the radius anomalies of planets such as TrES-4, and that the degree of heating is plausible if it is assumed that the orbital eccentricities of such systems are non-zero yet still consistent with the observational limits.

REFERENCES

- Bakos, G., Noyes, R. W., Kovács, G., Stanek, K. Z., Sasselov, D. D., & Domsa, I. 2004, *PASP*, 116, 266
- Barklem, P. S., Piskunov, N., & O'Mara, B. J. 2000, *A&AS*, 142, 467
- Böhm-Vitense, E. 2004, *AJ*, 128, 2435
- Burrows, A., Hubeny, I., Budaj, J., & Hubbard, W. B. 2007, *ApJ*, 661, 502
- Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997, *A&A*, 318, 841
- Collier Cameron, A., et al. 2006, *MNRAS*, 373, 799
- Collier Cameron, A., et al. 2007, *MNRAS*, 380, 1230
- Fortney, J. J., Marley, M. S., & Barnes, J. W. 2007, *ApJ*, 659, 1661
- Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, *A&AS*, 141, 371
- Gonzalez, G., Laws, C., Tyagi, S., & Reddy, B. E. 2001, *AJ*, 121, 432
- Gonzalez, G., & Laws, C. 2000, *AJ*, 119, 390
- Kurucz, R., & Bell, B. 1995, *Atomic Line Data* (R.L. Kurucz and B. Bell) Kurucz CD-ROM No. 23. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1995., 23
- Liu, X., Burrows, A., & Ibgui, L. 2008, *ApJ*, 687, 1191
- Magain, P. 1984, *A&A*, 134, 189
- Mandushev, G., et al. 2007, *ApJ*, 667, L195
- McCullough, P. R., Stys, J. E., Valenti, J. A., Fleming, S. W., Janes, K. A., & Heasley, J. N. 2005, *PASP*, 117, 783
- O'Donovan, F. T., Charbonneau, D., & Hillenbrand, L. 2006, *Bulletin of the American Astronomical Society*, 38, 1212
- Pollacco, D. L., et al. 2006, *PASP*, 118, 1407
- Santos, N. C., Israelian, G., & Mayor, M. 2004, *A&A*, 415, 1153
- Smalley, B. 2005, *Memorie della Societa Astronomica Italiana Supplement*, 8, 130
- Smalley B., Smith K. C., Dworetzky M. M., 2001, *UCLSYN Userguide*
- Smith K.C., 1992, PhD thesis, University of London
- Sozzetti, A., et al. 2008, *arXiv:0809.4589*

Valenti, J. A., & Fischer, D. A. 2005, *ApJS*, 159, 141